Discovering new physics with GW observations

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New Physics?

Pillars of modern physics:

General Relativity + Standard Model of Particle Physics

???

GR is generically singular and not renormalizable

Dark Matter

Dark Energy

The question is not whether there is new physics to be discovered, but rather at which scales it becomes important, if it is detectable and if so, where it will show up.

Outline

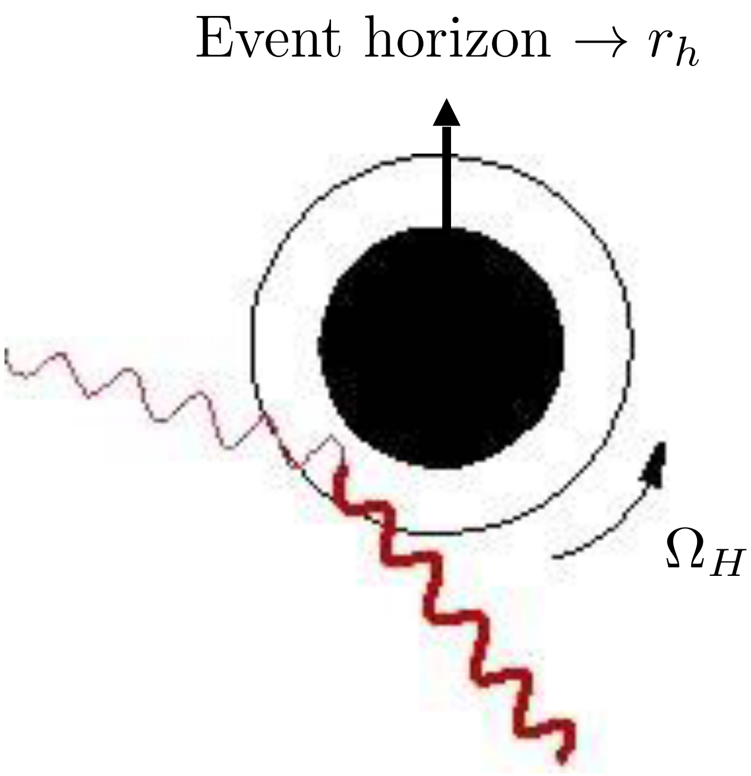
1) Superradiant instabilities & black holes as particle detectors

2) Exotic Compact Objects

Superradiant instabilities & black holes as particle detectors

Rotating BHs: Superradiance

Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74



$$\Phi(t,r,\theta,\phi) = \Psi(r) e^{-i\omega t + im\phi} P_l(\cos\theta)$$

$$\frac{\omega}{m} < \Omega_H$$

$$\Omega_H = \frac{J}{2 r_h M^2}$$

$J \rightarrow$ angular momentum

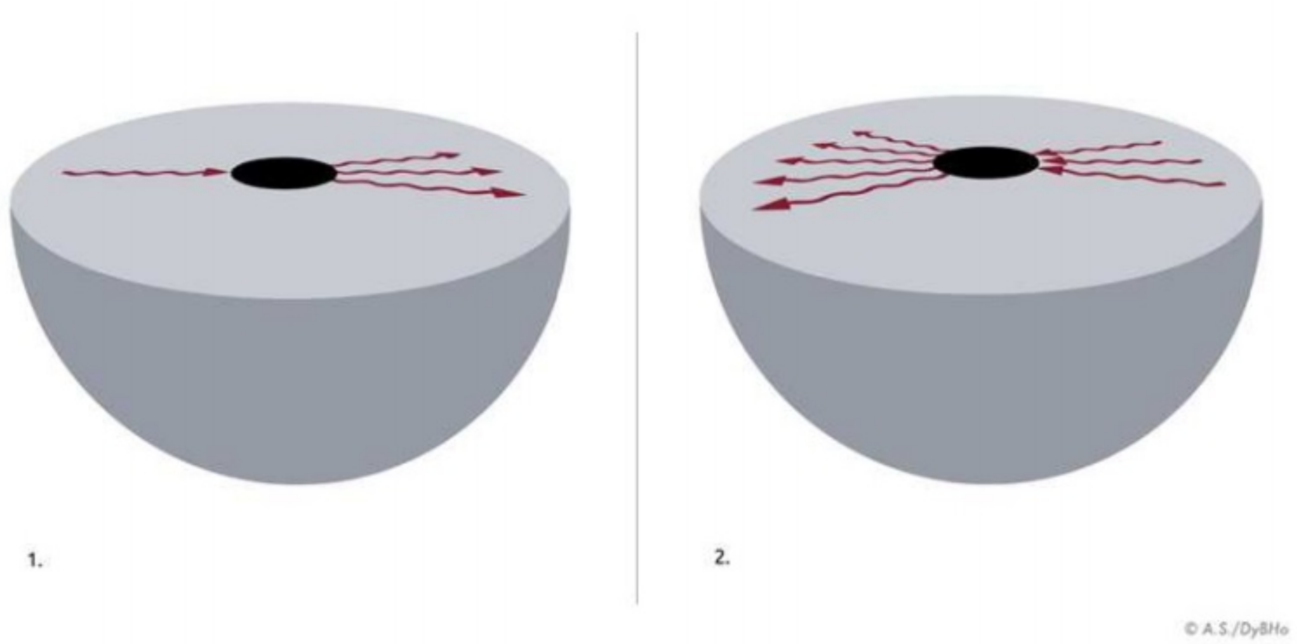
Amplified scattering of **bosonic** waves ⇨ Extraction of energy and angular momentum from the BH

Review: Brito, Cardoso & Pani, '15

Superradiant instability

Press & Teukolsky, '72

Confinement + Superradiance ⟶ Superradiant instability



Kerr surrounded by a perfectly reflecting mirror is unstable against bosonic radiation (includes gravitational radiation) with frequency:

$$\omega < m\Omega_H$$

Massive bosonic fields around Kerr

Detweiler , PRD22 (1980) 2323, Pani *et al*, PRD86 (2012) 104017, Witek *et al*, PRD87 (2013) 043513, RB, Cardoso & Pani, PRD88 (2013) 023514

- s=0,

$$\Box\Phi - \mu_S^2\Phi = 0$$

- s=1,

$$\begin{cases} \Box A_\nu - \mu_V^2 A_\nu = 0\,, \\ \mu_V^2 \nabla^\mu A_\mu = 0\,. \end{cases}$$

- s=2,

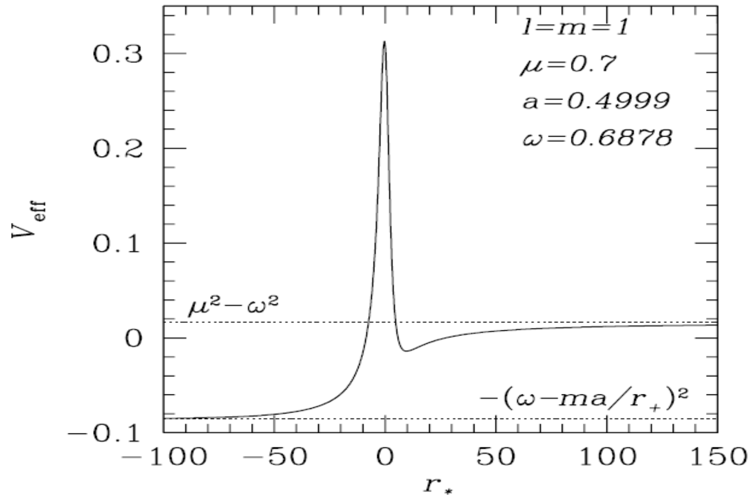
$$\begin{cases} \Box h_{\mu\nu} + 2R_{\alpha\mu\beta\nu}h^{\alpha\beta} - \mu_T^2 h_{\mu\nu} = 0\,, \\ \mu_T^2 \nabla^\mu h_{\mu\nu} = 0\,, \\ \mu_T^2 h = 0\,. \end{cases}$$

$$X_{\mu_1\ldots}(t,r,\vartheta,\varphi) = X_{lm}^{(i)}(r)\mathcal{Y}_{\mu_1\ldots}^{lm\,(i)}(\vartheta)e^{im\varphi}e^{-i\omega t}$$

$$\frac{d^2X}{dr_*^2} + (\omega^2 - V_{\rm eff})X = 0$$

$$\omega = \omega_R + i\omega_I$$

$$\begin{array}{lll} \omega_R & \sim & \mu \\ \omega_I & \propto & (m\Omega_H - \omega_R)\,(M\mu)^\alpha \end{array}$$



From: Cardoso & Yoshida, JHEP 0507 (2005) 009

Massive bosonic fields around Kerr are unstable when $\omega_R < m\Omega_H$.

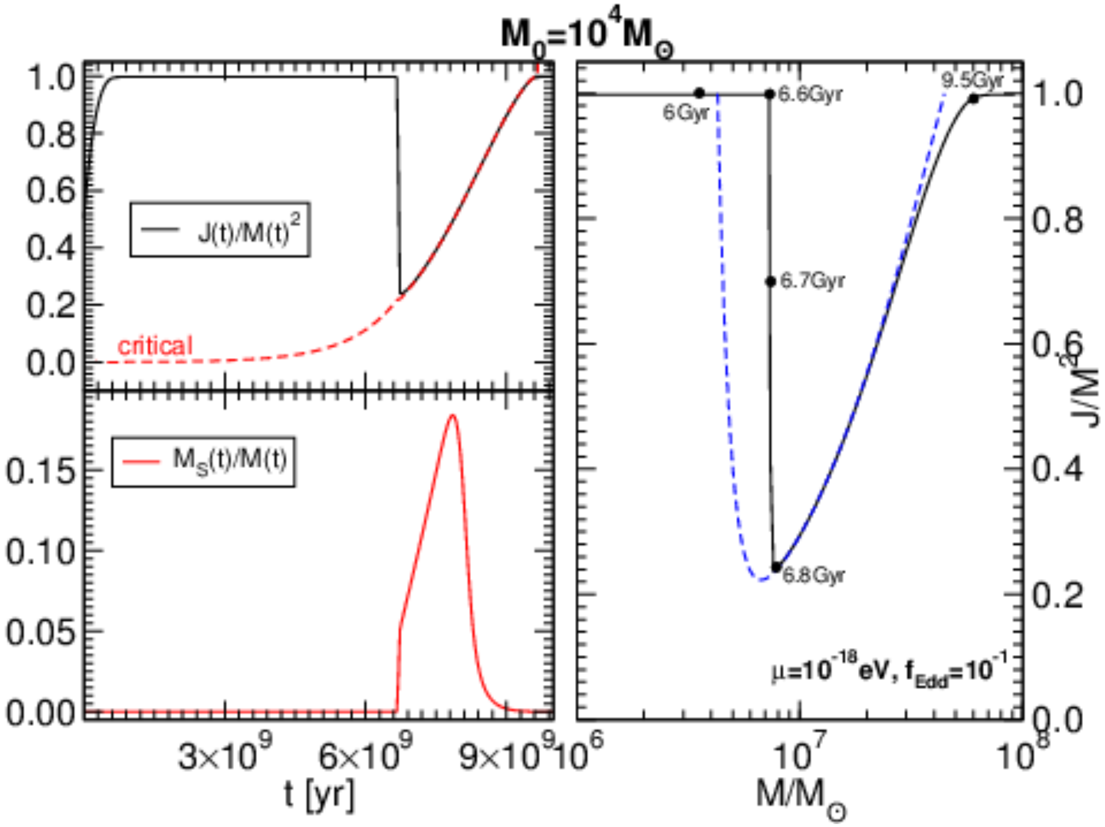
Relevant when $r_h/\lambda_c \lesssim 1$.

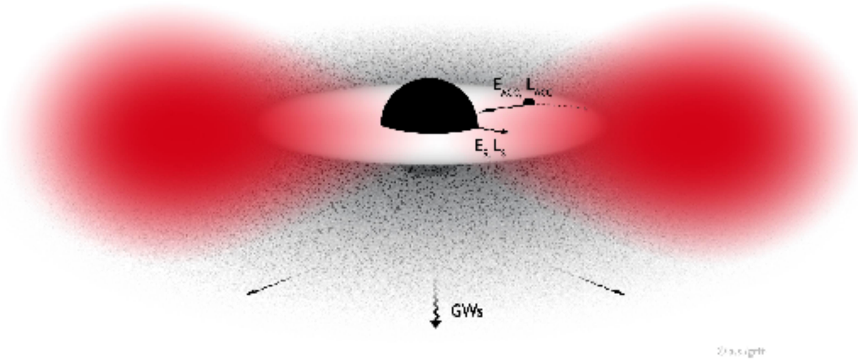
$$a \sim M\,,\ \mu_S \sim 0.42M^{-1} \sim 5.6\times10^{-17}\left(\frac{10^6 M_\odot}{M}\right)\text{eV}\,,\ \tau \sim 6.7\times10^6 M \sim \left(\frac{M}{10^6 M_\odot}\right)\text{yr}$$

Evolution of the superradiant instability

- End-state is still theoretically unknown, but we know that black hole slowly loses spin and mass due to the instability until reaching saturation $\omega_R = m\Omega_H$.

- Formation of long-lived bosonic condensates around BHs (or hairy black holes for complex scalar and vector fields Herdeiro & Radu '14; Herdeiro, Radu & Runarsson '16, SEE HERDEIRO'S TALK).

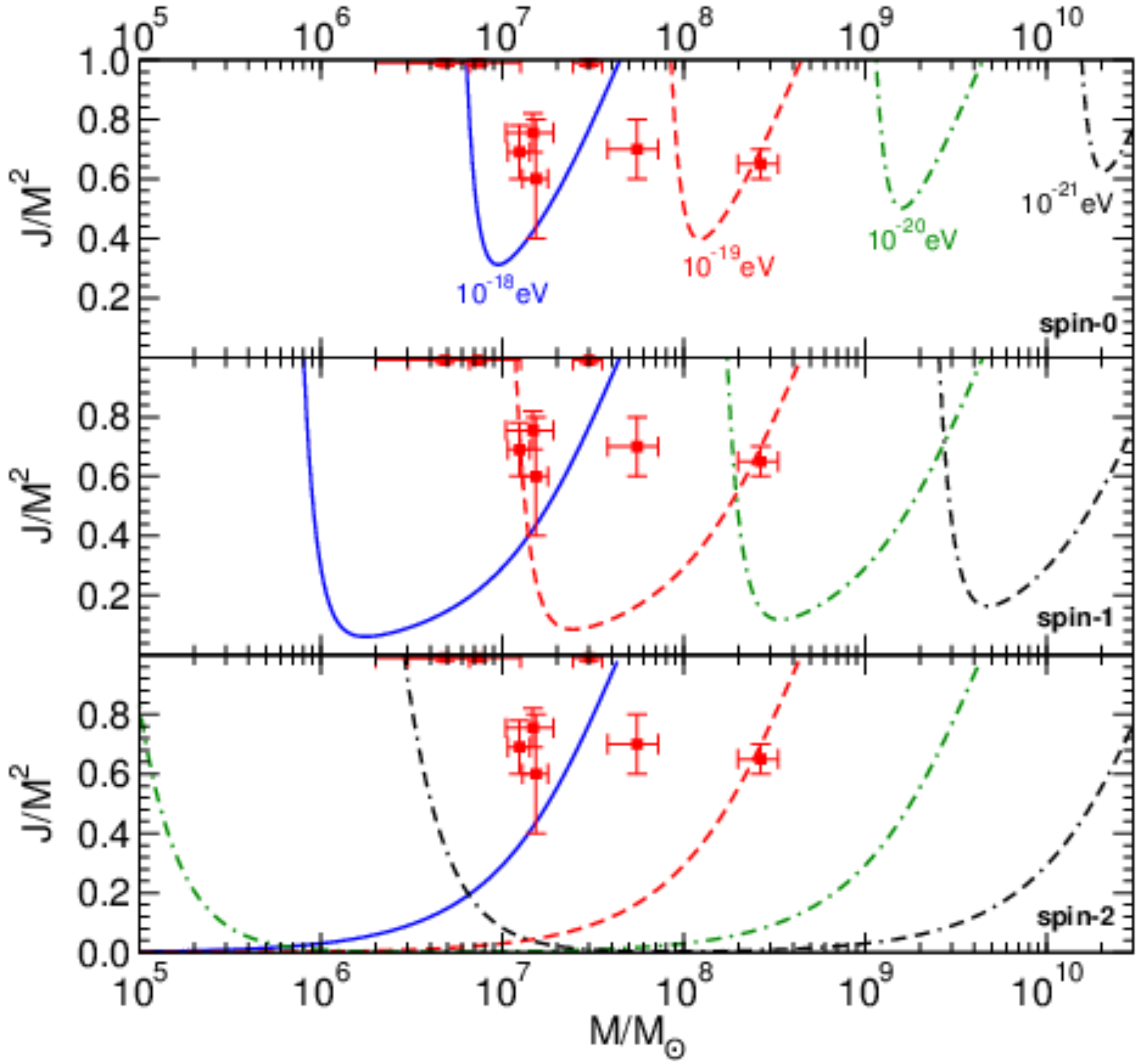




RB, Cardoso & Pani,'15

Bounds on light bosons

Arvanitaki & Dubovsky Phys.Rev. D83 (2011) 044026 , Pani *et al*, Phys.Rev.Lett. 109 (2012) 131102, Phys.Rev. D86 (2012) 104017, RB, Cardoso & Pani, Phys.Rev. D88 (2013) 023514



- QCD axion; String axiverse (Arvanitaki+ '10), …
- dark photons; hidden U(1) sector; massive photon
- massive graviton; bimetric theories of gravity;

Continuous gravitational-wave sources

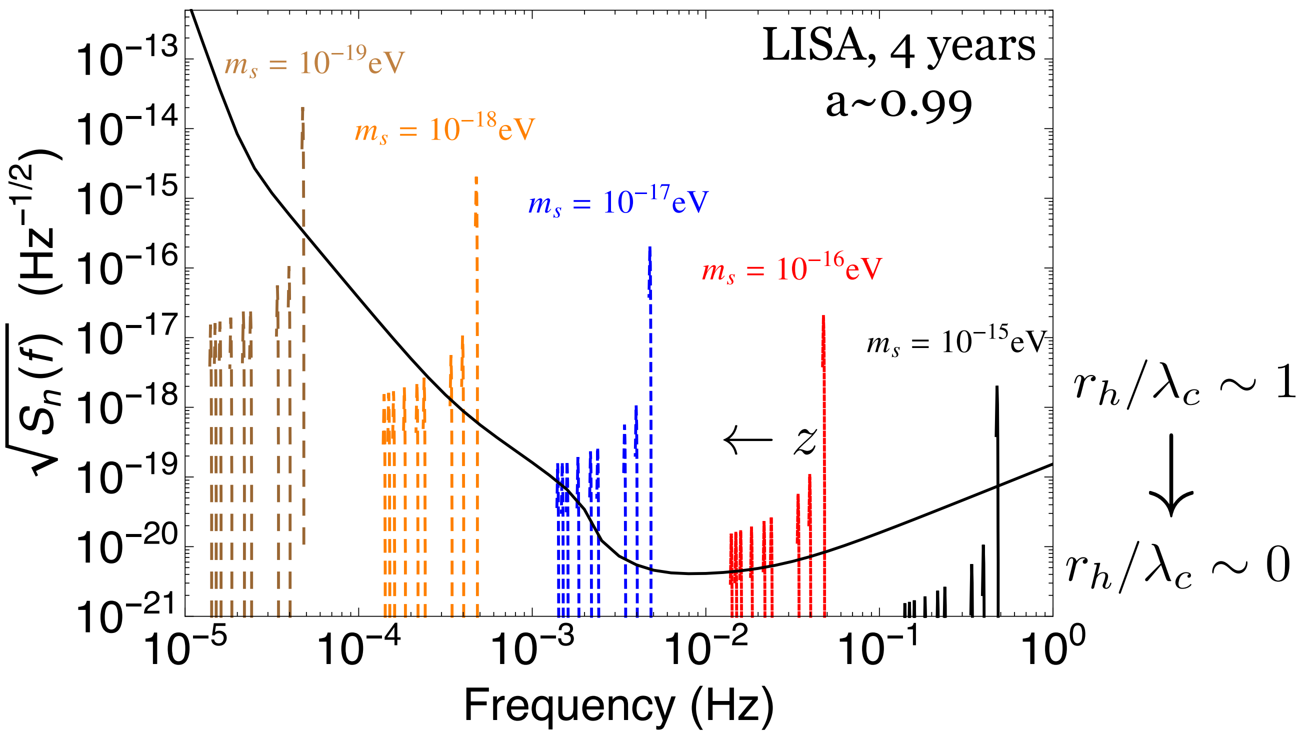
- Long-lived gravitational signals produced by real fields around black holes (Arvanitaki & Dubovsky , '11):

$$\Phi = \Re\left(\phi(r)S(\theta)e^{im\varphi}e^{i\omega_R t}\right)$$

$$T^{\mu\nu}_{\rm scalar} = -\frac{1}{4}\left(\Phi_{,\alpha}\Phi^{,\alpha} + \mu_S^2\Phi^2\right) + \frac{1}{2}\Phi^{,\mu}\Phi^{,\nu} \sim \Re\left(e^{2i\omega_R}e^{2im\phi}\right)$$

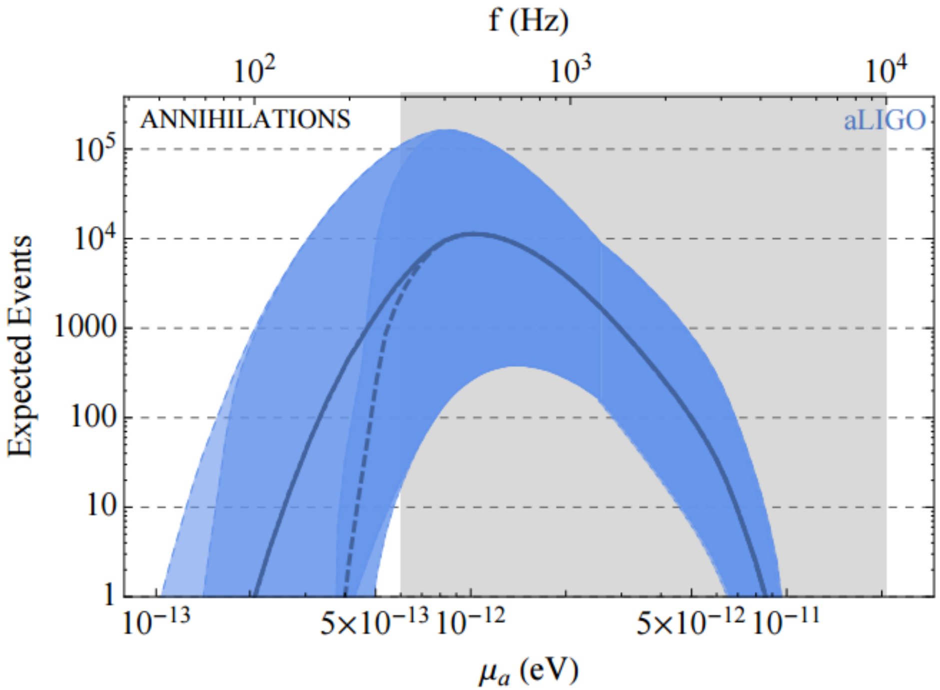
- GW frequency is set by the boson field mass: $f_{\rm GW} \sim 5\,{\rm mHz}\left(\frac{m_B c^2}{10^{-17}{\rm eV}}\right)$,

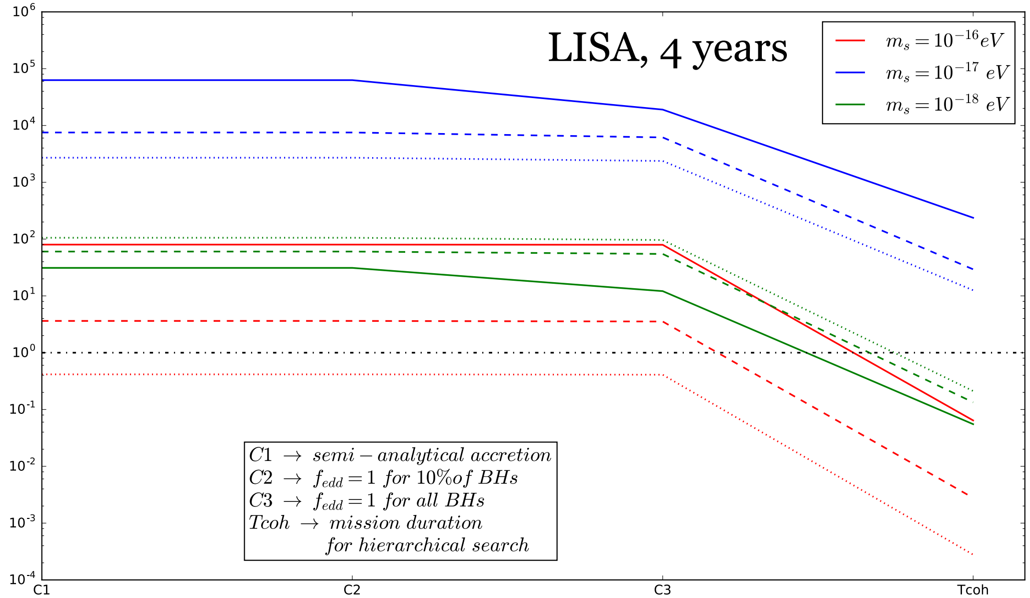
$$h \sim 8\times10^{-20}\left(\frac{a}{0.9}\right)\left(\frac{r_h/\lambda_c}{0.4}\right)^7\left(\frac{M_{BH}}{10^6 M_\odot}\right)\left(\frac{1{\rm Mpc}}{d}\right) \qquad t_{\rm GW} \sim 10^5\left(\frac{0.9}{a}\right)\left(\frac{0.4}{r_h/\lambda_c}\right)^{15}\left(\frac{M_{BH}}{10^6 M_\odot}\right)\text{ years}$$



All-sky searches

Arvanitaki, Baryakhtar & Huang, '15;
RB, Ghosh, Barausse, Berti, Cardoso, Pani & Klein, *work in progress*;



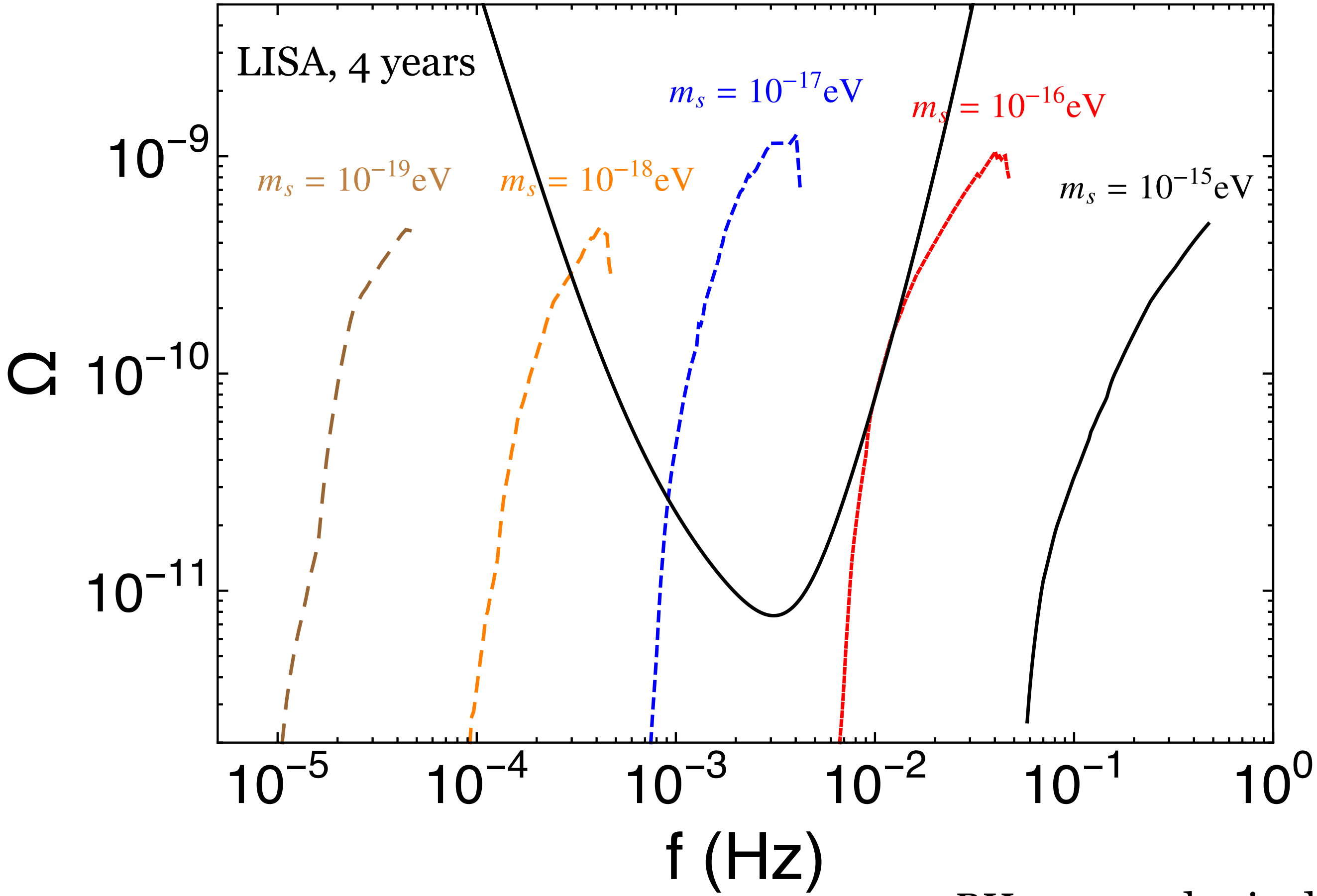


From: Arvanitaki, Baryakhtar & Huang, '15;

- LISA and aLIGO have the potential to detect up to thousands of events in all-sky searches for continuous gravitational waves.
- Main source of uncertainty comes from the mass and **spin** distribution of the black hole population.

Stochastic Background

RB, Ghosh, Barausse, Berti, Cardoso, Pani & Klein, *work in progress*



$$\Omega_{\rm gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\ln f}$$

BH mass and spin distribution: Sesana, Barausse, Dotti & Rossi arXiv:1402.7088

❖ The existence of many unresolved sources produces a potentially observable stochastic background **but** again large uncertainties in BH mass and spin distribution.

Exotic Compact Objects

Exotic compact objects

- Are there alternatives to black holes?
- Do they form under reasonable conditions?
- Are they stable?
- Can we distinguish them from black holes, e.g. through electromagnetic and gravitational wave signals?

ALTERNATIVES

- Boson stars, Proca stars, Oscillatons, Boson-Fermion stars
- Wormholes
- Gravastars
- ...

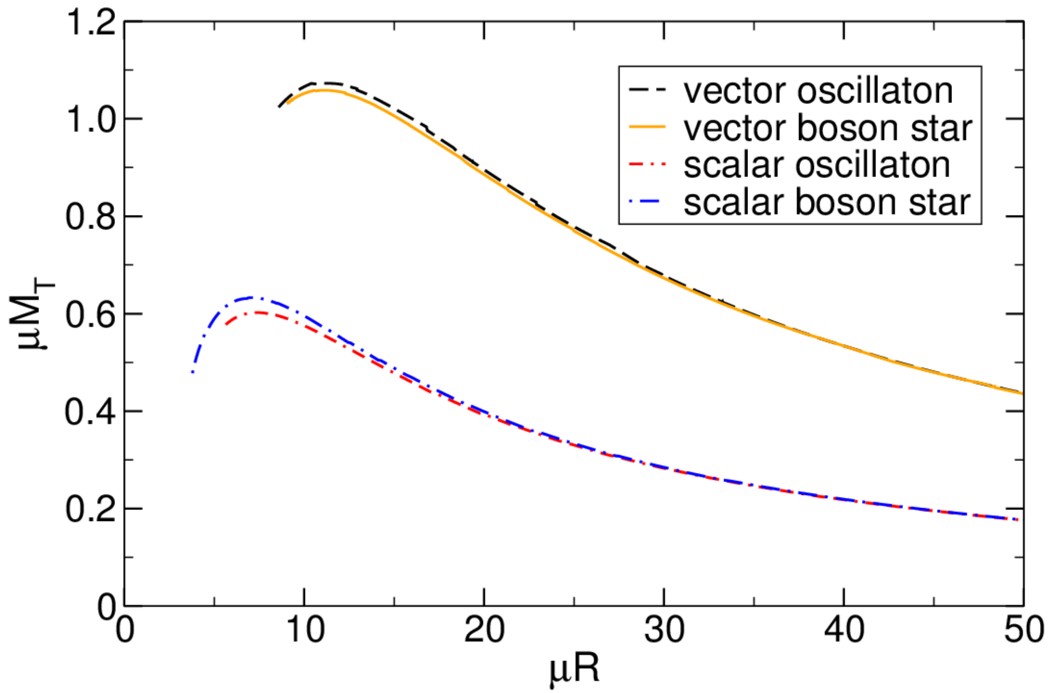
Boson/Proca stars & Oscillatons

D.J. Kaup '68; Ruffini & Bonazzola '69; Seidel & Suen '91;
RB, Cardoso, Herdeiro & Radu '15; RB, Cardoso, Macedo & Okawa '15;

$$\Box\Phi - \mu_S^2\Phi = 0$$

$$\begin{cases} \Box A_\nu - \mu_V^2 A_\nu = 0\,, \\ \mu_V^2 \nabla^\mu A_\mu = 0\,. \end{cases}$$

$$\frac{M m_B}{M_{pl}^2}$$



$$R/\lambda_c$$

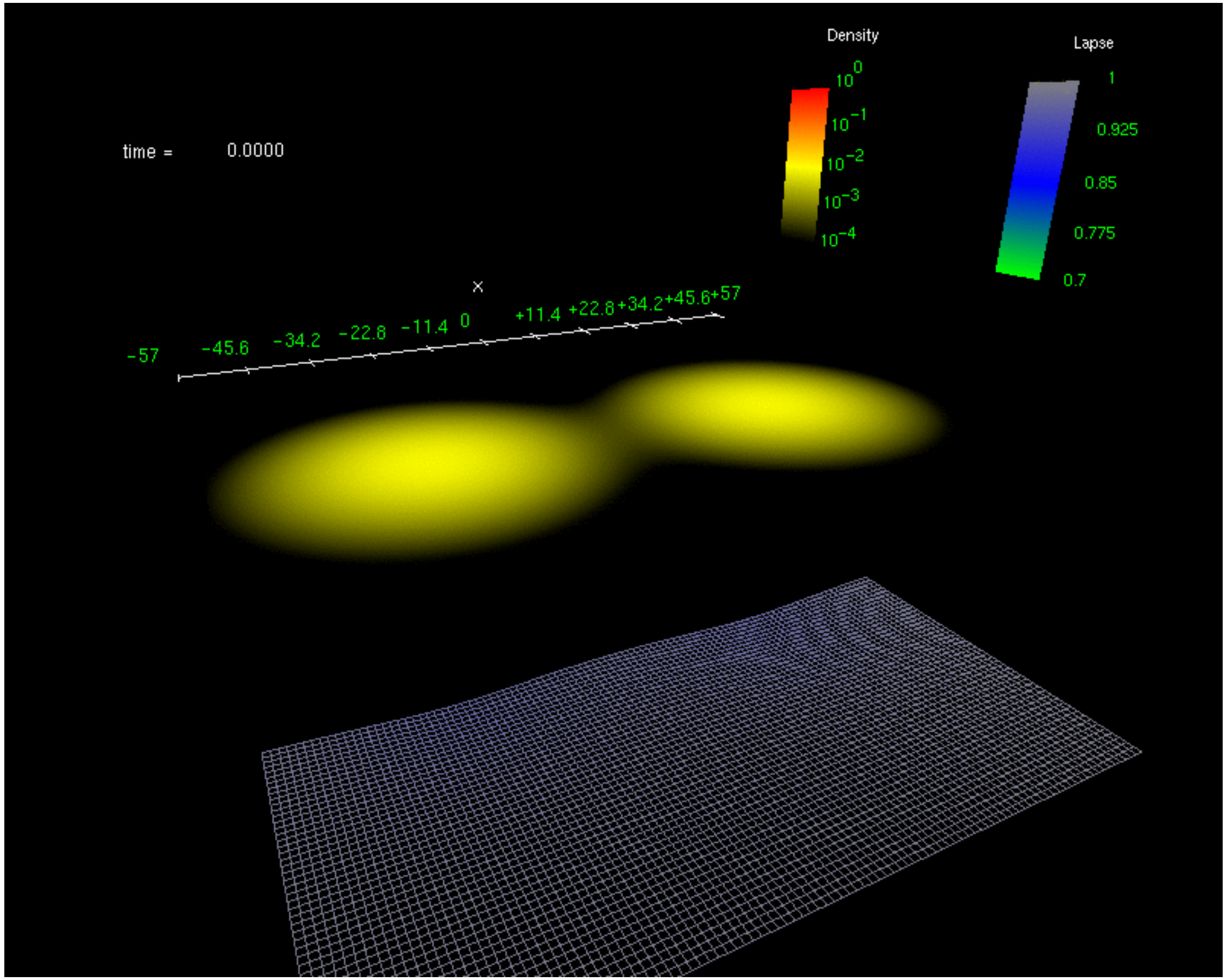
$$\frac{M_{\max}}{M_\odot} = 8\times10^{-11}\left(\frac{\text{eV}}{m_B c^2}\right)$$

Formation and growth

❖ Stable bosonic stars can form and grow

Equal-mass collision $M\mu \sim 0.3$.

Final mass $M\mu \sim 0.5$.



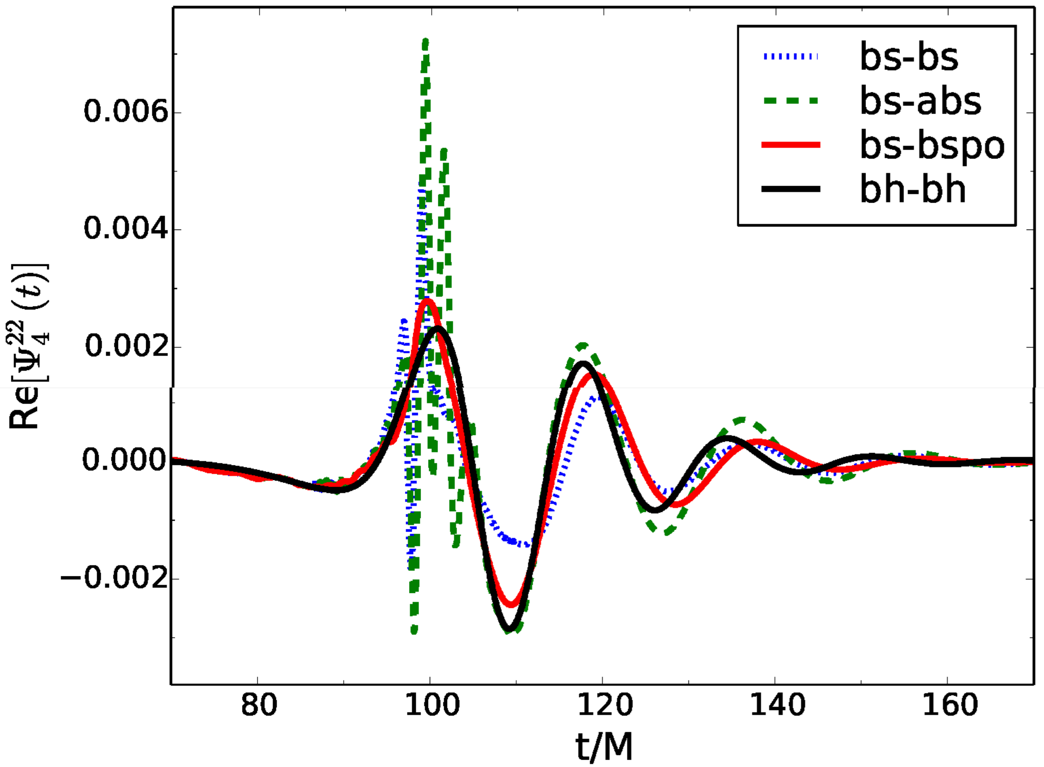
Credit: H. Okawa

GW emission

- GW emission by exotic compact objects remains a largely uncharted territory.

- Simulations of BS-BS inspiral exist but only for equal-mass systems (e.g. Palenzuela, Lehner & Liebling '07) and EMRIs (e.g. Kesden, Gair & Kamionkowski '07).

- Head-on collision simulations show that BS-BS can, in some cases, mimic BH-BH collisions.



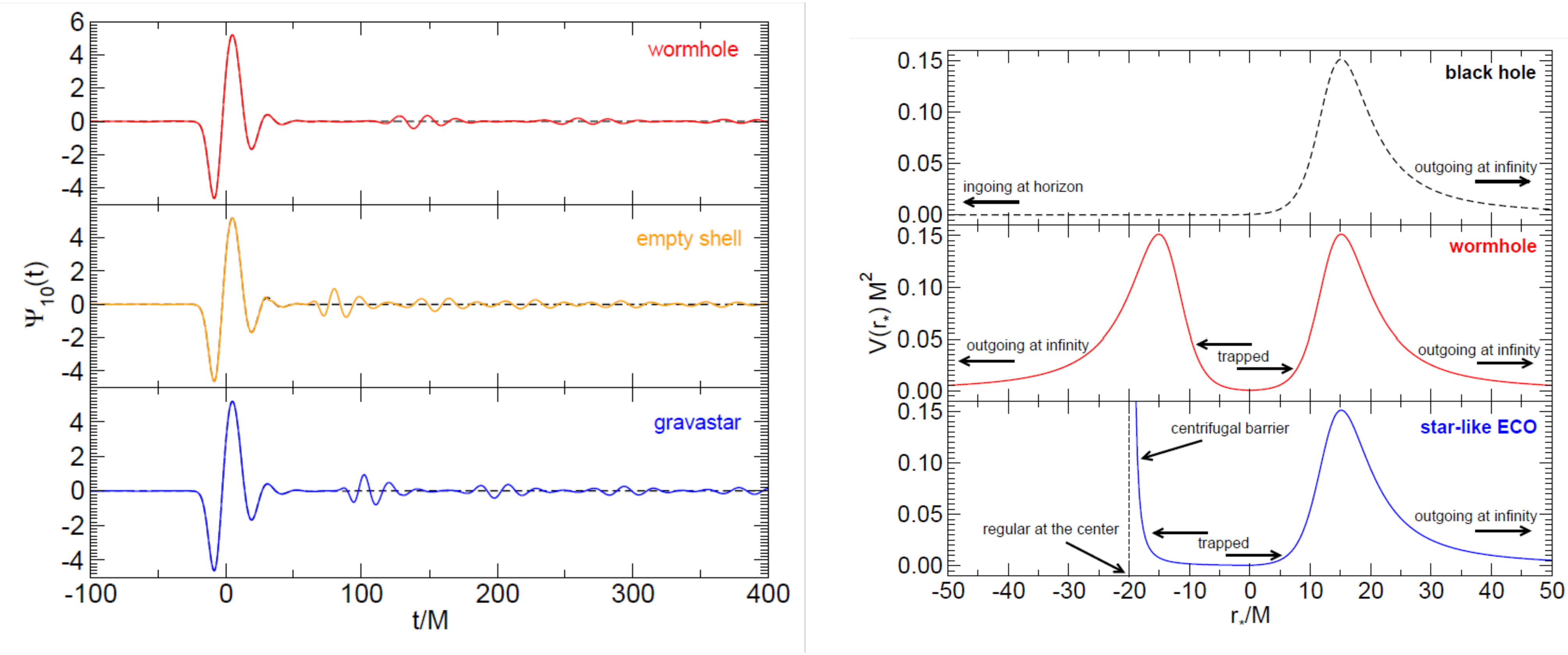
From: Cardoso, Hooper, Macedo, Palenzuela & Pani PRD94 084031

GW emission: echoes

- Ultra-compact horizonless objects can mimic the early ringdown signal of a perturbed BH. (Cardoso, Franzin, Pani '16)

- Late-time waveform is characterised by modulated and distorted "echoes".

$$\frac{d^2X}{dr_*^2} + (\omega^2 - V_{\text{eff}})X = 0$$



From: Cardoso, Hooper, Macedo, Palenzuela & Pani PRD94 084031

Conclusions

- Gravitational astronomy has the potential to give us unique hints for new physics.

- Superradiant instabilities can provide strong constraints on ultra-light bosons, turning black holes into effective particle detectors.

- Bosonic condensates around BHs can act as continuous gravitational wave sources.

- The *Kerr hypothesis* continues to be the best explanation for the observation of dark compact objects, but alternatives exist and more work is needed to completely rule them out.

Expect the unexpected…

Open issues

Black holes as particles detectors:

1) Can we distinguish bosonic fields with different spins?

2) Can non-linearities change the picture (e.g. mixing between modes, bosenova, …)?

ECOs:

1) Ultra-compact objects likely to be unstable and formation channels are hard to conceive. How seriously should we take them?

2) Does the echo picture remains the same for collisions of ~equal-mass ECOs?

3) Sistematic study of waveforms from collisions of bosonic stars is needed.